

SNAP: Supernova / Acceleration Probe. An Experiment to  
Measure the Properties of the Accelerating Universe

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# SNAP: Supernova / Acceleration Probe. An Experiment to Measure the Properties of the Accelerating Universe

## Abstract

A  $\sim 2$ -meter satellite telescope with a 1-square-degree optical imager, a small near-IR imager, and a three-channel near-UV-to-near-IR spectrograph can discover over 2000 Type Ia supernovae in a year at redshifts between  $z = 0.1$  and  $1.7$ , and follow them with high-signal-to-noise calibrated light-curves and spectra. The resulting data set can determine the cosmological parameters with precision: mass density  $\Omega_M$  to  $\pm 0.02$ , vacuum energy density  $\Omega_\Lambda$  to  $\pm 0.05$ , and curvature  $\Omega_k$  to  $\pm 0.06$ . The data set can test the nature of the “dark energy” that is apparently accelerating the expansion of the universe. In particular, a cosmological constant dark energy can be differentiated from alternatives such as “quintessence,” by measuring the ratio of the dark energy’s pressure to its density to  $\pm 0.05$ , and by studying this ratio’s time dependence. The large numbers of supernovae across a wide range of redshifts are necessary but not sufficient to accomplish these goals; the controls for systematic uncertainties are primary drivers of the design of this space-based experiment. These systematic and statistical controls cannot be obtained with other ground-based and/or space-based telescopes, either currently in construction or in planning stages.

## Introduction

In the past few decades the study of cosmology has taken some of its first major steps as an empirical science, combining concepts and tools from astrophysics and particle physics. The most recent of these results have already brought surprises. The universe’s expansion is apparently accelerating rather than decelerating as expected due to gravity. This implies that the simplest model for the universe – flat and dominated by matter – appears not to be true, and that our current fundamental physics understanding of particles, forces, and fields is likely incomplete.

The most clear evidence for this surprising conclusion comes from the recent supernova measurements of changes in the universe’s expansion rate that directly show the acceleration. These measurements indicate the presence of a new, mysterious energy component that causes acceleration. This conclusion, when taken together with current Cosmic Microwave Background measurements, or inflationary theory, is supported by current measurements of the mass density of the universe.

To address this new puzzle and begin to establish a solid cosmological picture, we propose a satellite experiment, SNAP, to carry out a definitive supernova study that will determine the values of the cosmological parameters and may unveil the unidentified accelerating energy. This experiment addresses these fundamental science questions with a necessary level of statistical and systematic rigor that cannot be matched by plausible alternatives, whether on the ground or in space.

This proposed supernova measurement will play a key role in the larger set of cosmological measurement approaches expected to yield results over the next decade. (This proposed satellite will also use some of these other approaches as part of its science mission.) Together these measurements will complement and cross-check our understanding of the cosmological model of the universe. Since the supernova approach is arguably the most direct and least model dependent, we expect it to provide a touchstone for this concordance of measurement results. Moreover, since this experiment is sensitive to the redshift range in which the accelerating energy is dominant, it will provide a nearly unique window on the properties of this entity of fundamental physics.

This experiment capitalizes upon the many recent advances in instrumentation and space technology to explore fundamental questions about the nature of our universe.

## Scientific Motivation and Background

### A Simple, Direct Approach to the Cosmological Parameters

Type Ia supernovae (SNe Ia) provide simple cosmological measurement tools. Each one is a strikingly similar explosion event whose physics can be analyzed in some detail from its light curve and spectrum as it brightens and fades. Most observed SNe Ia have nearly the same peak luminosity, and the variations that do exist can be correlated with other observables and hence calibrated to 5% in distance (??). The variation-corrected peak brightness (magnitude) is then a measure of the distance to the supernova.

Photons from the supernova are redshifted in exact proportion to the stretching of the universe during the period that a photon travels to us. Thus the comparison of SN Ia redshifts and magnitudes provides a particularly straightforward measurement of the changing rate of expansion of the universe: the apparent magnitude indicates the distance and hence time back to the supernova explosion, while the redshift measures the total relative expansion of the universe since that time.

This satellite project is designed to establish a Hubble-diagram (redshift vs. magnitude) plot dense with supernova events looking back over two-thirds the age of the universe. With such a history of the expansion of the universe we can determine the contributions of decelerating and accelerating energies—mass density  $\Omega_M$ , vacuum energy density  $\Omega_\Lambda$ , and/or other yet-to-be-studied “dark energies”—as the expansion rate changes over time.

This is an extremely transparent methodology. Almost everyone, even non-scientists, can appreciate and perhaps critique every step. Aside from the basic cosmological equations, there is no model dependence in this empirically-based method, and it is sensitive to only a few parameters of cosmology so there is no fit required in a large-dimensional parameter space. (Conversely, this method of course, does not help determine these other parameters, except by narrowing down the whole phase space, as discussed below.) This transparency is an unusual and important feature of this particular very fundamental measurement.

## The Current Results: Questions Answered and Posed by an Accelerating Universe

The cosmological results from the magnitude/redshift measurements of a few score SNe Ia already present surprises and puzzles (??). Most striking is the indication that we live in an accelerating universe, which must be dominated by a positive cosmological constant or other vacuum energy whose pressure is negative and large. The very simplest cosmological model, the Einstein-de Sitter ( $\Omega_M = 1$ ) universe, which is flat and has zero cosmological constant, is strongly inconsistent with the data. Of the two arguably next-simplest models, only the flat model with the cosmological constant,  $\Lambda$ , fits the data, while the low-mass open universe with zero  $\Lambda$  does not. (All of these statements can be made with very strong statistical confidence; even stretching the range of imagined systematic uncertainties, it is very difficult to fit the data without a cosmological constant in a flat universe.)

These current results immediately raise important questions. Although the data indicate that an accelerating dark energy density—perhaps the cosmological constant—has overtaken the decelerating mass density, they do not tell us the actual magnitude of either one. These two density values are two of the fundamental parameters that describe the constituents of our universe, and determine its geometry and destiny. The proposed satellite project is designed to obtain sufficient magnitude-redshift data for a large enough range of redshifts ( $0.1 < z < 1.7$ ) that these absolute densities can each be determined to unprecedented accuracy (see Figure 1). Taken together, the sum of these energy densities then provides a measurement of the curvature of the universe.

The current data also do not tell us the nature of the dark energy; all we know is that it must have a sufficiently negative pressure to cause the universe’s expansion to accelerate. Our one long-known physical model for the dark energy, the vacuum energy density that Einstein called “the cosmological constant,” presents difficult theoretical problems. Why, for example, is the vacuum energy density so small when compared to the natural energy scales of the particles and fields that would be expected to account for it: the values that are consistent with the current SN Ia results are  $10^{120}$  times smaller than the Planck scale. Moreover, why would a vacuum energy density that remains constant throughout history turn out just now to be within a factor of two or three of the mass energy density, which has fallen by many orders of magnitude since the Big Bang?

In response to these theoretical problems, several alternative physical models have been proposed as candidates for the dark energy. These models can generally be characterized by their equation of state,  $p = w\rho$  (the speed of light,  $c$ , is set to unity). The ratio of pressure to density,  $w$ , can be constant or time-varying depending on the model, and has a constant value of  $-1$  in the case of the cosmological constant. The current SN Ia data allow some crude constraints on the alternative dark energy models, since not all equations of state fit the data. With SNAP we can begin to study these alternative dark energy models in some detail, by determining  $w$  to much higher accuracy and by studying its evolution as a function of time.

The existence of a negative-pressure vacuum energy density is in remarkable concordance with combined galaxy cluster measurements (?), which are sensitive to  $\Omega_M$ ,

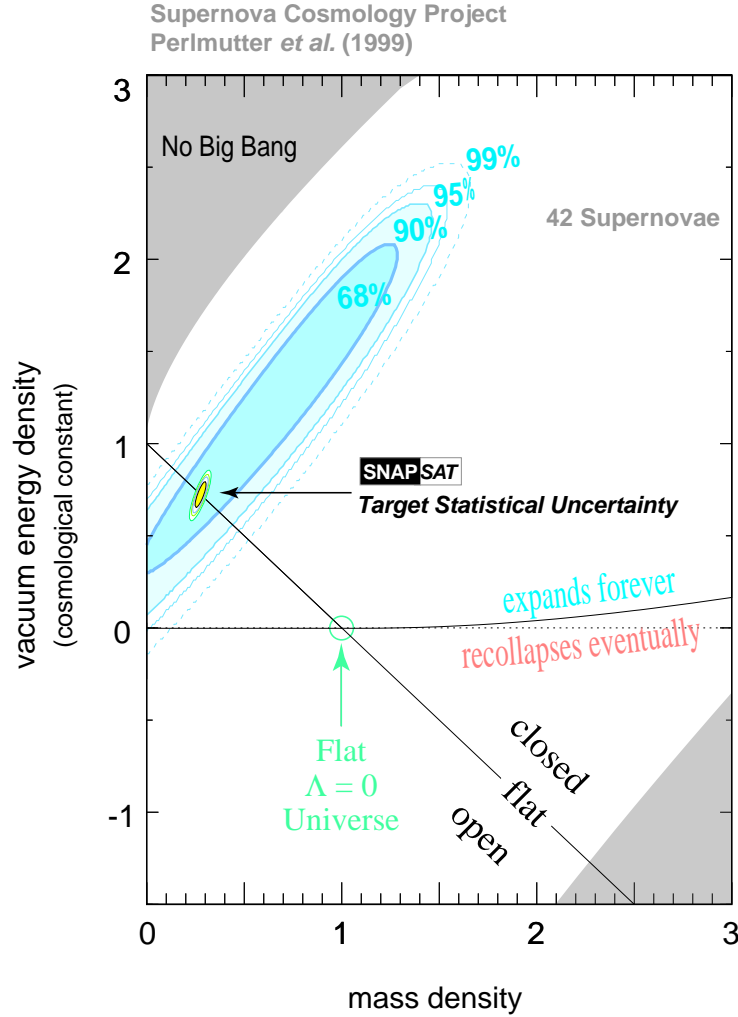


Figure 1: 68%, 90%, and 99% confidence regions in the  $\Omega_M$ — $\Omega_\Lambda$  plane from the 42 distant SNe Ia in ?. These results rule out a simple flat, [ $\Omega_M = 1$ ,  $\Omega_\Lambda = 0$ ] cosmology. They further show strong evidence (probability  $> 99\%$ ) for  $\Omega_\Lambda > 0$ . Also shown is the expected confidence region from the SNAP satellite for an  $\Omega_M = 0.28$  flat universe.

and current CMB results (??), which are sensitive to the curvature  $\Omega_k$  (see Figure 2). Two of these three independent measurements and standard Inflation would have to be in error to make the cosmological constant (or dark energy) unnecessary in the cosmological models. If this were, in fact, to be the case, a definitive accounting of

the systematic uncertainties for the supernova measurements would be particularly crucial, and any new cosmological models would still require the basic product of the SNAP mission, a history of the scale of the universe.

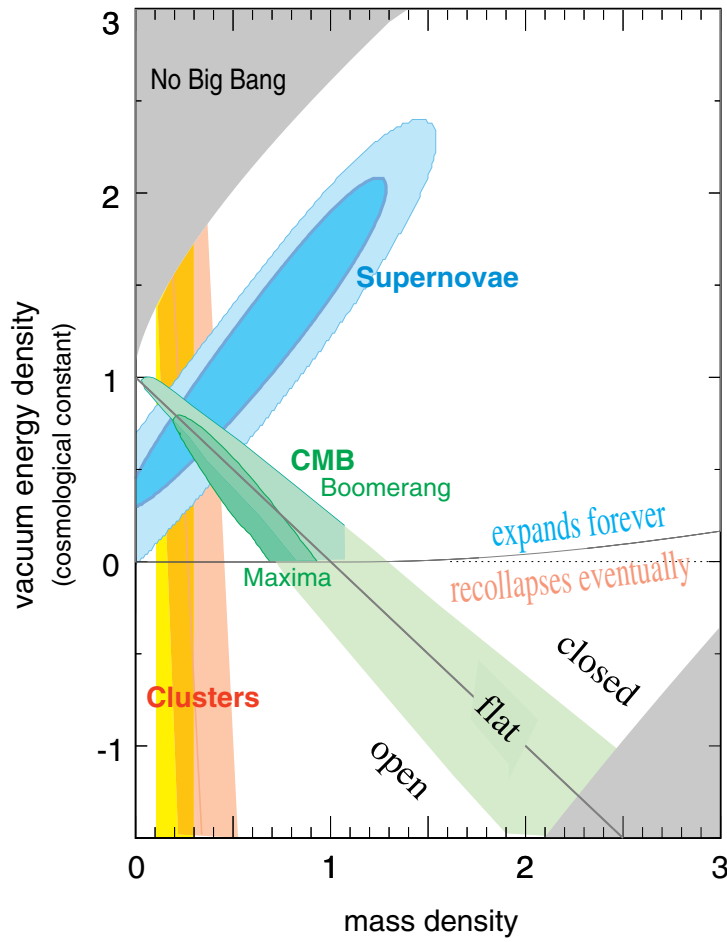


Figure 2: There is strong evidence for the existence of a cosmological vacuum energy density. Plotted are  $\Omega_M$ — $\Omega_\Lambda$  confidence regions for current SN, galaxy cluster, and CMB results. Their consistent overlap is a strong indicator for dark energy.

## Scientific Goals of SNAP

The primary scientific objective of this mission is to measure important cosmological parameters with low statistical and systematic errors. Assuming that the dark energy is the cosmological constant, this experiment can simultaneously determine mass density  $\Omega_M$  to accuracy of 0.02, cosmological constant energy density  $\Omega_\Lambda$  to 0.05 and curvature  $\Omega_k = 1 - \Omega_M - \Omega_\Lambda$  to 0.06.

The proposed experiment is one of very few that can study the dark energy directly, and test a cosmological constant against alternative dark energy candidates. Assuming a flat universe with mass density  $\Omega_M$  and a dark energy component with a non-evolving equation of state, the proposed experiment will be able to measure the equation-of-state ratio  $w$  with accuracy of 0.05, at least a factor of five better than the best planned cosmological probes. With such a strong constraint on  $w$  we will be able to differentiate between the cosmological constant and such theoretical alternatives as “topological defect” models and a range of dynamical scalar-field (“quintessence”) particle-physics models (see Figure 3). Moreover, with data of such high quality one can relax the assumption of the constant equation of state, and test its variation with redshift. A number of exciting investigations can then be done, including recovering the evolution of the equation of state with redshift and even the shape of the effective potential of the scalar field out to  $z \sim 1.5$ . These determinations would directly shed light on physics at high energy/small scale and physics of the early universe.

It is important to add that these SN Ia results are not the only available cosmological measurements, nor will they be at the time of launch of the proposed satellite. The estimates of the mass density from large-scale structure (LSS) surveys and cluster evidence are constantly improving. The MAP and Planck satellite experiments are expected to give high-precision fits of  $\sim 11$  cosmological and model-dependent parameters, both before and after the proposed satellite’s SN Ia measurements. Perhaps surprisingly, these supernova measurements will provide stronger constraints on  $\Omega_M$  and  $\Omega_\Lambda$  than those expected from either LSS or CMB measurements, and constraints on curvature  $\Omega_k$  that are comparable with those expected from MAP and Planck. The important cosmological test will be the cross comparison of these and other fundamental measurements — and it is even possible that cosmology will next progress when we discover that they do not agree. In any case, it will be all of these measurements fit simultaneously, that will provide us with our best understanding of the cosmology of the universe; the final results can be as much as an order of magnitude better than the constraints from any one measurement approach.

To accomplish these goals, it is not sufficient simply to discover and study more supernovae and more distant supernovae. The current SN Ia data set already has statistical uncertainties that are only a factor of two larger than the identified systematic uncertainties. There are also several additional proposed systematic effects that might confound attempts at higher precision, in particular the possibilities of “grey dust” or systematic shifts in the population of SN Ia host galaxy environments. Addressing each of these systematic concerns requires a major leap forward in the supernova measurement techniques, and has driven us to the satellite experiment described here.

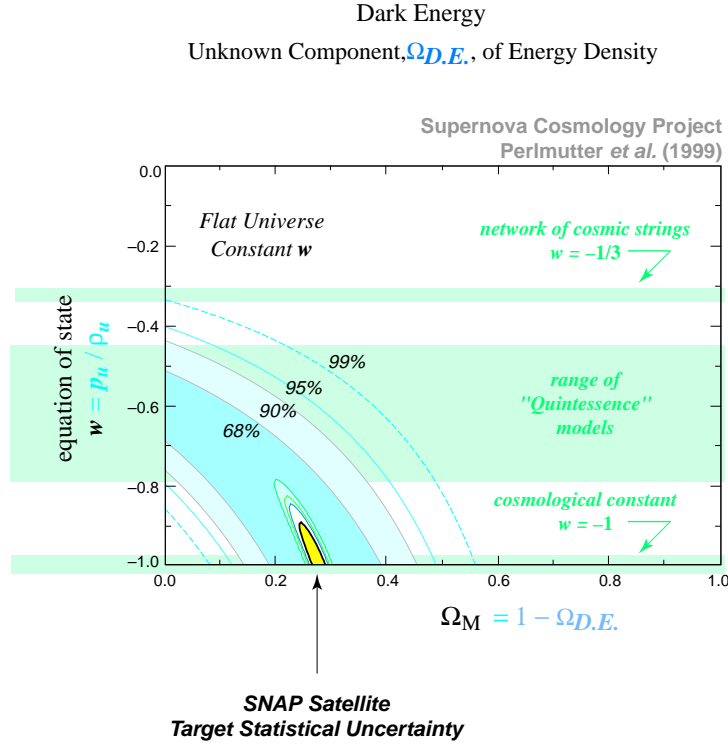


Figure 3: Best-fit 68%, 90%, 95%, and 99% confidence regions in the  $\Omega_M$ - $w$  plane for an additional energy density component,  $\Omega_w$ , characterized by an equation-of-state  $w = p/\rho$ . (If this energy density component is Einstein's cosmological constant,  $\Lambda$ , then the equation of state is  $w = p_\Lambda/\rho_\Lambda = -1$ .) Also shown is the expected confidence region allowed by SNAP.

## Proposed Experiment

### Instrumentation

The baseline proposed satellite experiment is based on a simple, dedicated combination of a 2.0-meter telescope, a 1-square-degree optical imager, a 1-square-arcminute near-IR imager, and a three-channel near-UV-to-near-IR spectrograph. The 1-square-degree wide field is obtained with a three-mirror telescope, and a feedback loop based on fast-readout chips in the focal plane to stabilize the image.

The wide-field imager is a billion pixel CCD mosaic (GigaCAM) for the wavelengths between 0.3 and 1.0 microns. The current imager design, GigaCAM, comprises 128, 3k x 3k, 10.5  $\mu\text{m}$  pixel, high resistivity, p-channel CCDs, being developed at the Lawrence Berkeley National Laboratory. The near-IR imager is a HgCdTe detector to obtain images of specific targets in the wavelengths between 1.0 and 1.7 microns.

The spectrograph uses dichroic beam-splitters to send the light into two optical channels (0.3 – 0.6  $\mu\text{m}$  and 0.55 – 1.0  $\mu\text{m}$ ) and one near-IR channel (0.95 – 1.7  $\mu\text{m}$ ). Each of the three channels employs an “integral field unit” (IFU) to obtain an effective image of a 2'' by 2'' field, split into 0.07'' by 0.07'' regions that are each individually sent to the spectrograph to obtain a flux at each position and wavelength (sometimes called a three-dimensional “data cube”). In operation, these integral field units will allow simultaneous spectroscopy of a supernova target and its surrounding galactic environment; the 2'' by 2'' field of view also removes any requirement for precise positioning of a supernova target in a traditional spectrograph slit. This point is particularly important for absolute flux calibration, because all of the supernova light is collected with the integral field units. The spectrograph is thus designed to allow the spectra to be used to obtain photometry in any “synthetic” filter band that one chooses.

## Observation Strategy and Baseline Data Package

This instrumentation will be used with a simple, predetermined observing strategy designed to monitor a 20-square-degree region of sky near the north and south ecliptic poles, discovering and following supernovae that explode in that region. Every field will be visited frequently enough with sufficiently long exposures that at any given redshift up to  $z = 1.7$  every supernova will be discovered within, on average, two restframe days of explosion. Every supernova at  $z < 1.2$  will be followed as it brightens and fades, while at  $z > 1.2$  there will be sufficient numbers of supernovae that it will only be necessary (and possible) to follow a subsample to obtain comparable numbers of supernovae.

The wide-field imager makes it possible to find and follow approximately 2000 SNe Ia in a year. The 2.0-meter aperture of the mirror, along with high throughput instruments, allow this dataset to extend to redshift  $z = 1.7$ .

This prearranged observing strategy will provide a uniform, standardized, calibrated dataset for each supernova, allowing for the first time comprehensive comparisons across complete sets of supernovae. The standardized dataset will have the following measurements that will address, and often eliminate, each of the statistical and systematic uncertainties that have been identified or proposed.

- A light curve sampled at frequent, standardized epochs that extends from  $\sim 2$  restframe days to  $\sim 80$  restframe days after explosion.
- Multiple color measurements, including optical and near-IR bands, at key epochs on the light curve.
- Spectrum at maximum light, extending from 0.3  $\mu\text{m}$  to 1.7  $\mu\text{m}$ .

- Final reference images and spectra to enable clean subtraction of host galaxy light.

The quality of these measurements is as important as the time and wavelength coverage, so we require:

- Control over signal-to-noise ratio for these photometry and spectroscopy measurements, to permit comparably high statistical significance for supernovae over a wide range of redshifts.
- Control over calibration for these photometry and spectroscopy measurements, with constant monitoring data collected to ensure that cross-instrument and cross-wavelength calibration remains stable over time.

Note that to date not one single SN Ia has ever been observed with this complete set of measurements, either from the ground or in space, and only a handful have a dataset that is comparably thorough. With the observing strategy proposed here, *every one* of  $\sim 2000$  followed SN Ia will have this complete set of measurements.

In addition to this minimum-required-dataset, a still more extensive set of observations will be performed for a randomly selected subset of SNe Ia (with more at lower redshifts and fewer at higher redshifts). These additional observations will include:

- A time series of spectra, sampled frequently over the entire 80 restframe days of the observed light curve.
- Multiple filter-band light curves. (These are not necessary when the time series of spectra is obtained, since this provides synthetic-filter photometry.)

## Control of Statistical and Systematic Uncertainties

The satellite instrumentation and observation strategy is designed to provide comprehensive control of the previously identified or proposed sources of uncertainty. The completeness of the resulting dataset will make it possible to monitor the physical properties of each supernova explosion, allowing studies of effects that have *not* been previously identified or proposed.

At present, the identified systematic uncertainty is over half the size of the statistical uncertainty; this would provide the “floor” on the proposed measurement uncertainty, if it were not improved. However, almost every one of the sources of identified systematics is due to limitations of the previous (and even planned NGST baseline SN program) measurements. The dataset described here removes these limitations so that the relevant effects can be measured and the previous systematic uncertainties now become controllable *statistical* uncertainties.

## Previously Identified Sources of Systematic Uncertainty

In Table 1, we summarize the identified sources of systematic error, and give the uncertainty that each contributed to previous measurements. With the proposed satellite experiment, each of these effects can either be measured so that it can become part of the statistical error budget, or else bounded (the target overall systematic uncertainty is kept below  $\sim 0.02$  magnitudes, so that it will contribute comparably to the final statistical uncertainties). The final column of the table summarizes the observations required to reach this target systematic uncertainty.

Systematic	Current ground-based $\delta M$	SNAP requirement to satisfy $\delta M < 0.02$
Malmquist bias	0.04	Detection of every supernova 3.8 magnitudes below peak in the target redshift range
K-Correction and Cross-Filter Calibration	0.025	Spectral time series of representative SN Ia and cross-wavelength relative flux calibration
Non-SN Ia Contamination	$< 0.05$	Spectrum for every supernova at maximum covering the rest frame Si II 6250Å feature
Milky Way Galaxy extinction	$< 0.04$	SDSS & SIRTf observations; SNAP spectra of Galactic subdwarfs
Gravitational lensing by clumped mass	$< 0.06$	Average out the effect with large statistics with $\sim 75$ SNe Ia per 0.03 redshift bin. SNAP microlensing measurements.
Extinction by “ordinary” dust outside the Milky Way	0.03	Cross-wavelength calibrated spectra to observe wavelength dependent absorption

Table 1: Listed are the main systematic errors in the measurement of the cosmological parameters. Their contribution to magnitude uncertainties in the current analyzed data set is tabulated, along with the observational requirements needed to reduce those uncertainties to  $\delta M < 0.02$

## Proposed Sources of Systematic Uncertainty

**Extinction by Proposed “Gray Dust”:** Models of “gray dust” have been proposed to evade detection by the usual measurements of reddening (?). However, even

gray dust cannot remain completely invisible, since it will re-emit absorbed light and contribute to the far-infrared (FIR) background. Current SCUBA observations indicate that FIR emission from galaxies is close enough to account for all the FIR background. Deeper SCUBA and SIRTf observations should tighten the constraints on the amount of gray dust allowed.

Another tell-tale observation will allow us to independently detect and measure gray dust. The physical models so far proposed have dust grains that are large enough that they dim blue and red light equally, however the near-IR light ( $\sim 1.2 \mu\text{m}$ ) is less affected. The same technique can therefore be used to measure this dust as would be used to measure the “ordinary” dust, by extending the broad-wavelength measurements into the near-IR. This will measure dimming due to proposed large-grain gray dust out to  $z = 0.5$ , and this proposed systematic uncertainty, too, can become part of our statistical error budget.

Current space-based observations of existing supernovae are already being used in this way to test if gray dust in a non-accelerating universe can mimic the effects of an accelerating universe at  $z = 0.5$ . Results show that the observed color excess is too small to be compatible with the 30% opacity of gray dust needed in a  $\Lambda = 0$  universe to be consistent with observations. Our proposed satellite measurements would improve greatly on these first results and allow detection and measurement of much smaller gray-dust opacity.

*Requirement: Cross-wavelength calibrated spectra, at controlled SN-explosion epochs, that extend to rest-frame  $1.2 \mu\text{m}$ .*

In principle, gray dust models can be constructed that would evade these broad-wavelength measurements, either because the “gray dust” does not exist closer than  $z = 0.5$  or because the dust grains are even larger than first proposed and thus absorb light equally at  $0.4 \mu\text{m}$  and  $1.2 \mu\text{m}$ . (Such larger grain sizes are strongly disfavored by other astrophysical constraints, however.) Even these more contrived dust models can be measured by the proposed dataset because of its large redshift range: at redshifts beyond  $z = 1.4$  models with dust would be distinguished from cosmological models with no dust but with  $\Lambda$  at the 50 standard-deviation level.

*Requirement: A redshift distribution that extends to  $z \geq 1.5$  for followed SNe Ia.*

**Proposed Uncorrected Evolution:** Uncorrected “evolution” has also been proposed as a potential source of systematic uncertainty (?). Supernova behavior may depend on properties of its progenitor star or binary-star system. The distribution of these stellar properties is likely to change over time—“evolve”—in a given galaxy, and over a set of galaxies.

As galaxies age, generation after generation of stars complete their life-cycles, enriching the galactic environment with heavy elements (the abundance of these elements is termed “metallicity”). In a given generation of stars, the more massive ones will complete their life cycles sooner, so the distribution of stellar masses will also change over time. Such statistical changes in the galactic environments are expected to affect the typical properties of supernova-progenitor stars, and hence the details of the triggering and evolution of the supernova explosions. Even the SNe Ia might be ex-

pected to show some differences that reflect the galactic environment in which their progenitor stars exploded, even though they are triggered under very similar physical conditions every time (as mass is slowly added to a white dwarf star until it approaches the Chandrasekhar limit).

Evidence for such galactic-environment driven differences among SNe Ia has in fact already been seen among nearby, low-redshift supernovae (?). The range of intrinsic SN Ia luminosities seen in spiral galaxies differs from that seen in elliptical galaxies. So far, it appears that the differences that have been identified are well calibrated by the SN Ia light curve width-luminosity relation. The standard supernova analyses thus already are correcting for a luminosity effect due to galactic-environment-distribution evolution. There are likely to be additional, more subtle effects of changes in the galactic environment and shifts in the progenitor star population, although it is not clear that these effects would change the peak luminosity of the SNe Ia. The proposed satellite experiment is designed to provide sufficient data to measure these second-order effects, which might be collectively called “proposed uncorrected evolution.”

In this discussion it is important to recognize that each individual galaxy begins its life at a different time since the Big Bang, at a different absolute time. Even today, there are newly formed, “young,” first-generation galaxies present that have not yet gone through the life cycles of their high-mass stars, nor yet produced significant heavy element abundance. Thus at any given redshift there will be a large range of galactic environments present and the supernovae will correspondingly exhibit a large range of progenitor-star ages and heavy-element abundances. (This is why we can currently observe and correct an evolutionary range of SNe Ia using only low-redshift, nearby SNe Ia.) It is only the relative distribution of these environment ages that will change with universal clock time. By identifying matching sets of supernova that come from essentially the same progenitor stars in the same galactic environments, but across a wide variety of redshifts, we can then perform the cosmological measurements using SNe Ia in the same evolutionary state. This only requires that the SN Ia sample sizes are sufficiently large and varied at each redshift that we can find matching examples in sufficient quantities.

We have identified a series of key supernova features that respond to differences in the underlying physics of the supernova. By measuring all of these features for each supernova we can tightly constrain the physical conditions of the explosion, making it possible to recognize sets of supernovae with matching initial conditions. The current theoretical models of SN Ia explosions are not sufficiently complete to predict the precise luminosity of each supernova, but they are able to give the rough relationships between changes in the physical conditions of the supernovae (such as opacity, metallicity, fused nickel mass, and nickel distribution) and changes in their peak luminosities. We can therefore give the approximate accuracy needed for the measurement of each feature to ensure that the physical condition of each set of supernovae is well enough determined so that the range of luminosities for those supernovae is well below the systematic uncertainty bound ( $\sim 2\%$  in total).

In addition to these features of the supernovae themselves, we will also study the host galaxy of the supernova. We can measure the host galaxy luminosity, colors, morphology, type, and the location of the supernova within the galaxy, even at redshifts

$z \sim 1.7$ . These observations are not possible from the ground.

## Why a New Satellite?: Design Requirements and Ground- or Space-Based Alternatives

The science goals that we have described drive the design requirements of this experiment. The target statistical uncertainties are closely matched to the target systematic uncertainties, so that the numbers of supernovae, their redshift range, and the quality and comprehensive nature of the dataset of measurements for each supernova all together can achieve the stated cosmological measurements.

In particular, the mirror aperture is about as small as it can be before spectroscopy at the requisite resolution is no longer zodiacal-light-noise limited. A smaller mirror design would quickly degrade the achievable signal-to-noise of the spectroscopy measurements, and drastically reduce the number of supernovae followed. The field of view for the optical imager has been optimized to obtain the follow-up photometry of multiple supernovae simultaneously; a smaller field would require multiple pointings of the telescope and again would greatly reduce the number of supernovae that could be followed. The three-channel spectrograph covers precisely the wavelength range necessary to capture, over the entire target redshift range, the Si II 6250 Å feature that both identifies the SNe Ia and provides a key measurement of the explosion physics to identify each supernova’s evolutionary state. In general, more than one critical design requirement has driven each of these instrument choices; for example, the wavelength range of the spectrograph also is required to measure the effects of any “gray dust” on the supernova magnitudes.

Precision measurements of the cosmological parameters and their properties place stringent requirements on both statistical and systematic errors. SNAP’s unpolluted, high signal-to-noise, ambitiously targeted photometric and spectroscopic data preclude the use of ground-based observatories and thus require a satellite-borne telescope.

The primary obstacle to achieving high signal-to-noise, precise photometric data from ground-based observations is the brightness of the night sky. Photometrically, the bright sky emission not only contributes Poisson noise but also exacerbates background non-uniformity (e.g. flatfield errors). These two errors place redshift limits on light-curve measurements critical for the determination of extinction and supernova progenitor properties. For example, three-hour ground-based observations with an 8-m telescope are unable to make very early discoveries ( $\sim 2$  days after explosion in the supernova rest frame) beyond  $z = 0.55$ , nor would they provide precision measurements of the light curve plateau at 2.8 mag below peak brightness for  $z > 0.7$  supernovae. Color measurements critical for extinction determination could not be made at the requisite 0.02 mag precision (which propagates to a  $\sim 0.1$  mag uncertainty in the corrected magnitude) beyond  $z = 0.75$ . Although using larger aperture telescopes will decrease the contribution of Poisson noise, they would have little effect on the errors from background non-uniformity.

Atmospheric OH emission and water absorption are characterized by many strong,

Requirements	Addresses and Resolves
Detection of every supernova 3.8 magnitudes below peak for $z \leq 1.5$	<ul style="list-style-type: none"> <li>• Rise time measurement</li> <li>• Eliminates Malmquist Bias</li> </ul>
SNe Ia at $0.3 \leq z \leq 1.7$	<ul style="list-style-type: none"> <li>• Statistics and lever-arm for the precision measurement of <math>\Omega_M, \Omega_\Lambda</math></li> <li>• Detection of Gray Dust</li> <li>• Detection of SN Ia evolution</li> </ul>
$\sim 75$ SNe Ia per 0.03 redshift bin	<ul style="list-style-type: none"> <li>• Statistics and lever-arm for the precision measurement of <math>w</math></li> <li>• The effect of gravitational lensing by clumped mass is averaged out</li> </ul>
Well sampled light-curves between $\sim 2$ restframe days to $\sim 80$ restframe days after explosion	<ul style="list-style-type: none"> <li>• Determination of the peak magnitude of each SN Ia</li> <li>• Determination of the light-curve shape of each SN Ia</li> <li>• Detection of SN Ia evolution</li> </ul>
Multiple IR and optical color measurements at key epochs	<ul style="list-style-type: none"> <li>• Determination of extinction for each SN Ia</li> <li>• Confirmation of the light-curve shape of each SN Ia</li> </ul>
Spectrum for every supernova at maximum covering the rest frame Si II 6250Å feature and that extend from rest frame UV to $1.2\mu\text{m}$	<ul style="list-style-type: none"> <li>• Eliminates non-SN Ia contamination</li> <li>• Measures extinction due to “ordinary” dust outside the Milky Way</li> <li>• Spectral feature – peak magnitude relation</li> </ul>
Spectral time series of representative SN Ia with cross-wavelength relative flux calibration	<ul style="list-style-type: none"> <li>• Determine K-corrections</li> <li>• Allow cross-filter comparisons</li> <li>• Detection of Gray Dust</li> <li>• Detection of SN Ia evolution</li> </ul>

Table 2: Observational requirements to ensure various statistical and systematic errors each contribute uncertainties of  $\delta M < 0.02$ . The particular sources of error that each requirement addresses are also listed.

sharp lines and cover the important near-IR region where the optical light of distant supernovae is redshifted ( $0.7 - 1.8 \mu\text{m}$ ). The brightness and variability of the NIR sky along with non-linear and variable H<sub>2</sub>O absorption pose a severe challenge to accurate photometry of distance SNe free of systematic error. Moreover, H<sub>2</sub>O absorption will decimate key spectral features — especially the Si 6150 Å feature that defines the SN Ia class — for many distant SNe.

There are a number of secondary but important disadvantages in running a supernova program from the ground. The degraded seeing from atmospheric scattering not only increases Poisson errors within the seeing disk but also increases our susceptibility towards systematic errors from the host galaxy. Ground-based searches have a day–night duty cycle, are susceptible to bad weather, and suffer from moonlight. This combination strongly diminishes our search efficiency and renders impossible the measurement of periodically sampled light curves and spectroscopic time series of distant supernovae.

Adaptive optics for the wide field required for multiplexed follow-up and searching is not foreseeable in the near future; a reduction in the field of view of the optical imager severely limits the number of supernovae that can be discovered and followed. This is incompatible with one of our main goals of discovering large numbers of supernovae to explore SN Ia subclasses and significantly improve on ground-based statistical errors. Precision broadband photometry using OH suppression methods is impossible without a priori knowledge of the source spectral energy distribution which in the case of supernovae is time dependent and may evolve as a function of redshift.

Given this inherent limitation of ground-based observations, a comparison with plausible ground- and space-based alternatives makes it particularly clear why this satellite design is required to achieve the science. Simply finding the supernovae near their explosion date from the ground is the first challenge, even for an entirely dedicated 8-meter telescope with a special-purpose 9-square-degree imager. To detect SNe Ia within  $\sim 2$  restframe days of explosion (as required for the risetime measurement) the photometry must extend to 3.8 magnitudes below peak with a signal-to-noise of 10. From the ground, with its bright sky and atmospheric seeing, this limits the search to redshifts less than  $z = 0.6$ —and fewer than 300 SNe Ia per year would be measured. If one begins to degrade the experiment by removing this risetime measurement’s control on systematics, the next key requirement is a measurement of the plateau phase of the light-curve, approximately 2.8 magnitudes below peak, which would limit ground-based searches to redshifts less than  $z = 0.7$ . Finally, if we give up this plateau-measurement control on systematics, the fundamental measurement requirement is 2% photometry at peak and 15 days after peak (to determine lightcurve width). From the ground, even this minimal dataset is only obtainable to redshifts less than  $z = 0.75$ . (See Table 3 for a summary of these comparisons.)

Using the existing Hubble Space Telescope or even the planned Next Generation Space Telescope (NGST) does not improve the ability to discover these supernovae, since neither telescope has a wide-field camera. With the 8-meter NGST’s 16-square-arcminute field of view, it would require tens of years of full-time searching to obtain a comparable sample of SNe Ia in the target redshift range. The NGST does have a quite useful supernova program planned, but all at higher redshifts than this project,

and without the extensive controls on systematic uncertainties that we require. This NGST program is aimed at different science, since it is not possible to study the “dark energy” at redshifts much beyond  $z \sim 1.2$ , when the universe had smaller scale and the matter-density dominated.

One might wonder if the NGST could be used simply to follow up the spectroscopy of the supernovae discovered with this telescope. This would be possible, but it is a rather wasteful use of the 8-meter’s capabilities; most of time for over half a year would be spent simply slewing the NGST from supernova to supernova, with the shutter open for only a small fraction of the time. (A coordinated wide-field ground-based search with NGST follow-up would suffer this same problem and further add the disadvantages of discovering the higher-redshift supernova late after explosion.)

Search	Facilities Photometry + Spectra	Batch	SNe/yr	$z$ Limit given time budget	Early Discovery (2 days)	Time (hrs) to Achieve S/N at max $z$	Magnitude Limit (AB)
SNAP	SNAP	Yes	2400	$z < 1.7$	Yes	4 ( $S/N = 3$ )	30
HST+ACS	HST+ACS+NIC	Yes	20	$z < 1.7$	Yes	2 ( $S/N = 3$ )	30
NGST	NGST	No	60	$z < 1.7$	Yes	0.1	-
CFHT	HST+ACS+NIC	No	350	$z < 0.6$	4 day	8 ( $S/N = 5$ )	26
WFT	Keck+AO	No	140	$z < 1.2$	Peak-0.5	8 ( $S/N = 10$ )	26
WFT	WFT	Yes	210	$z < 0.6$	Yes	6 ( $S/N = 3$ )	27
WFT	NGST	No	430	$z < 0.6$	4 day	8 ( $S/N = 10$ )	26
WFT	NGST	No	460	$z < 0.9$	6 day	7 ( $S/N = 5$ )	26.5
OWLT	OWLT	Yes	420	$z < 0.7$	Yes	9 ( $S/N = 5$ )	27.5
OWLT	OWLT+AO+OH	No	290	$z < 1.0$	5 day	4 ( $S/N = 5$ )	27

Table 3: Comparison of alternative facilities to SNAP for baseline mission.

## Overview of Feasibility

The essential elements of the project’s feasibility have already been studied. We were able to establish many of the baseline design feasibility issues by reference to other satellite missions that have successfully flown, or are currently being built.

- We made a top-down cost estimate based on other similar satellite designs and costs.
- We performed a study of orbit options . We found several options that allowed a workable combination of launch vehicle, mass-to-orbit, thermal control, cosmic-ray load, continuous observing duty cycle, telemetry rates, and power budget.
- We have baselined a three-mirror anastigmat telescope design which provides a diffraction limited wide field of view with minimum obscuration. We are also likely to adopt a flight-proven lightweight glass mirror technology.
- Pointing requirements can be met two ways: (1) using feedback from the focal plane detectors to the spacecraft attitude control system, or (2) using a fast-steering mirror. Both are legacy technologies developed for earth-observing satellites. This image-stabilizing option avoids the need to maintain a precisely stable spacecraft.

- At University of California at Berkeley and at Lawrence Berkeley National Laboratory’s microfabrication facility, we have built and tested high-resistivity CCDs that provide greater than 90% quantum efficiency up to  $1\ \mu\text{m}$ , and are at least ten times more radiation hard than conventional CCDs. This fabrication process has now been transferred to a high-volume commercial vendor, and two fabrication runs are currently in their final stages of processing.
- For some years, much larger CCD and silicon strip arrays have been routinely built by the high energy physics community and operated in comparably inaccessible locations, where they are exposed to high radiation levels.
- We have conducted extensive simulation and modeling of the science reach and performance of various observing strategies and instrument trade-offs.

Our collaboration has the technical experience and competence to formulate, implement, and manage a successful satellite-borne mission. The University of California Space Sciences Laboratory, in particular, has a long tradition in satellite experiments, and has been responsible for project management, spacecraft, scientific packaging, mission and science operations, and ground station operations. Recent and current satellite missions in which collaboration members have played key roles include the Cosmic Background Explorer, the Extreme Ultra-Violet Explorer, the Fast Auroral Snapshot Explorer, and the High Energy Solar Spectroscopic Imager Spacecraft.

## Summary of Other Major Science

The dataset of images and spectra obtained with this wide-field imager and three-channel spectrograph can address other important science goals with very little additional effort in data collection or in the instrument specifications. Although these science goals will not be discussed in detail in this preview document, it is important in particular to note that we can obtain complementary measurements of the cosmological parameters with completely independent measurement methods.

**Weak lensing.** Because the observation strategy observes the same patches of sky repeatedly over a year of supernova observations, a very deep, high-resolution image can be added together from thousands of images taken at every orientation of the spacecraft. This is an ideal way to look for weak-lensing elongations of distant galaxies, since the optical distortions of the image will be small and well characterized. Such images of several dozen square-degree fields can constrain the cosmological parameters (see § ??) in a manner complementary to the SN Ia measurements, with different systematics.

**Type II supernovae.** As we discover and follow the SNe Ia, we will also discover and have the option of following SNe II. While these supernovae are not of predictable luminosity, they are close enough matches to a black body that their luminosities can be determined from the size and temperature of their photospheres, along with a fit to

any spectral deviations from black body. (Since our experiment provides a very tight constraint on the date of explosion and the velocity of the expanding gas, the size of the photosphere will be easy to determine.) Most SNe II are about six times fainter than the prototypical SNe Ia, so most will not be studied with early detections beyond redshifts  $z \sim 0.5$ . However since SNe II are much more frequent than SNe Ia, we can afford to study the brightest few percent and this will extend the SN II study beyond  $z = 1$ . The sources of systematic uncertainty for these SNe II measurements would generally be different from the SNe Ia systematic uncertainties.

There is also important science to be gained from this project that is not aimed specifically at the cosmological models. It is clear, for example, that the final set of very deep, wide field images would become a resource for all of astrophysics, as the Hubble Deep Fields have been.

## Timelines

We envision this satellite project as a two-stage process, consisting of a first study phase followed by a final design and construction phase. In Phase I, we will prepare a ZDR (“zeroth-order design report”) and full cost and schedule analysis for Phase II within 18 months, followed by a CDR (“conceptual design report”) which will describe in detail all technical aspects of the experiment to be presented in 30 months. We would expect both of these reports to be the basis for project reviews when they are presented.

Phase I would complete the equivalent of NASA “Phase A” and the first part of “Phase B” concept studies which would advance the design and critical technologies to a state of readiness that would minimize cost, schedule and technical risk for the construction phase that follows. Examples of current development activities include CCD commercialization and telescope optics design. In addition, we are currently in the process of selecting a spacecraft bus vendor.

During this same Phase I period, the ground-based studies will be carried forward to provide empirical support for the final science design of the SNAP mission. Further theoretical analyses of supernovae and their galactic environments will also contribute at this stage.

The fundamental questions and surprising discoveries of recent years make this a fascinating new era of empirical cosmology. This proposed satellite project presents a unique opportunity to extend this exciting work and advance our understanding of the universe. The origin and destiny of the universe have intrigued humanity for at least as long as there are written records. We live at a time when we can begin to find answers.